MODIS Reflective Solar Bands Calibration Algorithm and On-orbit Performance

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ABSTRACT

The MODerate Resolution Imaging Spectroradiometer (MODIS) is one of the key instruments for the NASA s Earth Observing System (EOS). The MODIS ProtoFlight Model (PFM) was launched on-board the EOS Terra spacecraft on December 18, 1999 and has been providing the science community and public users global data sets for the study of the land, oceans, and atmosphere for more than two and a half years. This coverage is further enhanced by the data sets from the MODIS Flight Model (FM-1) that was launched on-board the EOS Aqua spacecraft on May 4, 2002. MODIS has 36 spectral bands with wavelengths ranging from 0.41 to 14.5µm and nadir spatial resolutions of 250m (2 bands), 500m (5 bands), and 1km (29 bands). The sensor s 20 reflective solar bands (RSB) from 0.41 to 2.1µm are calibrated on-orbit by a solar diffuser (SD) and a solar diffuser stability monitor (SDSM) system. The other 16 thermal emissive bands (TEB) with wavelengths above 3.7µm are calibrated by a blackbody. This paper describes the RSB on-orbit calibration approach using the SD/SDSM system, its implementation in the Level 1B algorithm, and the RSB on-orbit characterization and performance for both Terra and Aqua MODIS. The TEB calibration algorithm and performance are presented in a separate paper in these proceedings.

Keywords: Terra, Aqua, MODIS, calibration, solar diffuser, solar diffuser stability monitor

1. INTRODUCTION

The Earth Observing System spacecraft EOS/Terra and EOS/Aqua, launched on December 18, 1999 and May 4, 2002 respectively, view Earth from sun-synchronous polar orbits at an altitude of 705km. The equator crossing time of the Terra spacecraft is 10:30 AM (local time, descending node) and that of the Aqua spacecraft is 1:30 PM (local time, ascending node). The MODerate Resolution Imaging Spectroradiometer (MODIS) ProtoFlight Model (PFM) is on-board the Terra spacecraft and the Flight Model (FM-1) is on-board the Aqua spacecraft. Both instruments have been providing global data sets for the study of the land, oceans, and atmosphere with morning and afternoon observations[1-2]. MODIS has 36 spectral bands with wavelengths ranging from 0.41 to 14.5µm and nadir spatial resolutions of 250m (2 bands), 500m (5 bands), and 1km (29 bands). MODIS heritage sensors include the Advanced Very High Resolution Radiometer (AVHRR), the Coastal Zone Color Scanner (CZCS), the Sea-viewing Wide Field of View Sensor (SeaWiFS), and the High Resolution Infrared Radiation Sounder (HIRS)[3-4]. Its design and technology development have been served as the pathfinder for the next generation sensors, such as the Visible/Infrared Imaging Radiometer Suite (VIIRS) in the National Polar-Orbiting Operational Environment Satellite System (NPOESS)[5].

The MODIS 20 reflective solar bands (RSB) cover the wavelengths from 0.41 to 2.1µm. These bands are calibrated on-orbit by a solar diffuser (SD) and a solar diffuser stability monitor (SDSM) system. In this paper we focus on the RSB on-orbit calibration methodology and its implementation in the Level 1B algorithm. We also show the on-orbit calibration results and the instrument performance for the RSB in both Terra and Aqua MODIS. The other 16 thermal emissive bands (TEB) with wavelengths above 3.7µm are calibrated by an on-board blackbody. The algorithm description and on-orbit performance for the TEB are presented by Xiong *et. al.* in a separate paper in these proceedings[6].

2. INSTRUMENT BACKGROUND

2.1 General Features

The MODIS is a two-sided paddle-wheel scanning spectral radiometer with a scan period of 1.478s which measures upwelling visible (VIS), near infrared (NIR), short wave infrared (SWIR), middle wave infrared (MWIR), and long wave infrared (LWIR) radiance. The Earth view scanning range of —55° to +55° about the instrument nadir produces a swath of 2330km along scan by 10km (at nadir) along track each scan. The spacecraft s orbital period is roughly 100 minutes and thus performs 14.4 orbits per day which allows the MODIS to observe the full Earth surface in less than 2 days. The Earth scene is viewed by 36 spectral bands, located on four focal plane assemblies (FPAs) with spatial resolutions at nadir of 250m (bands 1-2), 500m (bands 3-7), and 1km (bands 8-36). The delivered product of the reflected solar bands (RSB: VIS, NIR, and SWIR) is the reflectance factor for the Earth scene whereas the delivered product of the thermal emissive bands (TEB: MWIR and LWIR) is top of the atmosphere (TOA) radiance. In addition to the Earth view sector (EV, 1354 frames), each MODIS scan contains 4 calibration sectors: the solar diffuser sector (SD, 50 frames), the spectroradiometric calibration assembly sector (SRCA, 10 frames), the blackbody sector (BB, 50 frames), and the space view sector (SV, 50 frames). The MODIS instrument scan cavity and the on-board calibrators (OBCs) are shown in Figure 1. The SV sector provides data for dark scene subtraction at a scan-by-scan frequency. The SD is the primary on-orbit calibrator for the RSB while the BB is the primary on-orbit calibrator for the TEB. The SRCA is the primary calibrator for the VIS/NIR bands spectral response shift and for the sensor s band-to-band registration. Previous reports by Barnes *et. al.* have provided detailed description of MODIS instrument and its pre-launch characterizations[3-4].
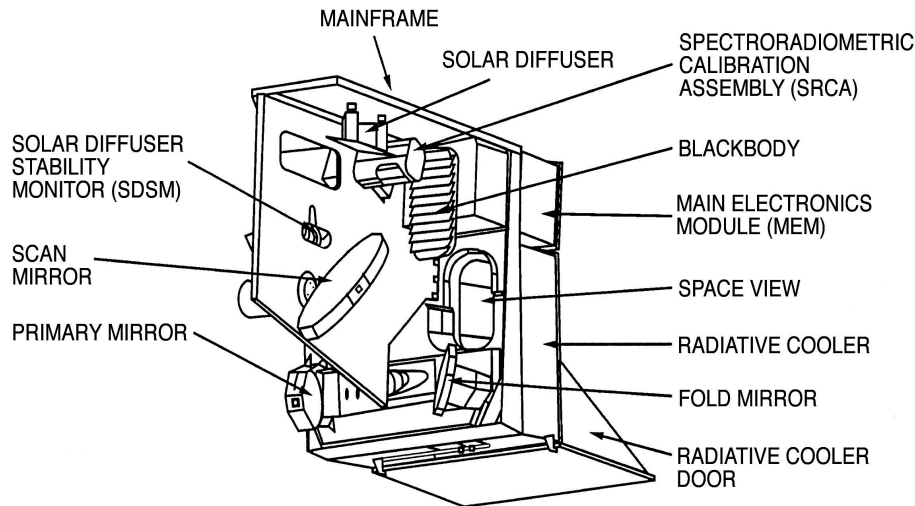

Figure 1: MODIS scan cavity and on-board calibrators: solar diffuser (SD), solar diffuser stability
monitor (SDSM), Blackbody (BB), and spectroradiometric calibration assembly (SRCA)

2.2 The Reflected Solar Bands

There are 20 reflective solar bands (RSB). The key specifications of the RSB are given in Table 1, including the spectral band center wavelength, typical scene radiance, and the corresponding signal-to-noise ratio (SNR). Two of the 1km bands, 13 and 14, are measured at both low and high gains through the use of time-delay and integration. Each 1km band has 10 detectors aligned in the along track direction, each 500m band has 20 detectors and 250 m bands 40 detectors. The scene swath of each scan is 2330km cross track (1354 frames or samples for the 1km bands) by 10km along track at nadir. For each 1km frame, there are 4 sub-samples collected by the 250m bands (bands 1-2) and 2 sub-samples by the 500m bands (bands 5-7). Both Terra and Aqua MODIS instruments are calibrated on orbit periodically using a solar diffuser/solar diffuser stability monitor system (SD/SDSM). Each calibration is performed on the individual band, detector, sub-frame, and mirror sides, yielding a total of 1340 calibration values.

Band	CW (nm)	Ltyp (W/m^2/sr/μ)	SNR (spec.)	SNR Terra (A-I)	SNR Terra (B)	SNR Terra (A-II)	SNR Aqua (B)
1	645	21.8	128	196	177	205	201
2	858	24.7	201	519	483	662	536
3	469	35.3	243	326	317	344	325
4	555	29.0	228	342	314	327	323
5	1240	5.4	74	97	120	133	154
6	1640	7.3	275	427	378	377	491
7	2130	1.0	110	89	85	95	156
8	412	44.9	880	1018	961	1029	1066
9	443	41.9	838	1383	1426	1296	1320
10	488	32.1	802	1359	1350	1259	1615
11	531	27.9	754	1334	1317	1308	1215
12	551	21.0	750	1199	1190	1224	1178
13L	667	9.5	910	1195	1214	1189	1223
14L	678	8.7	1087	1313	1329	1403	1328
15	748	10.2	586	1207	1276	1180	1303
16	869	6.2	516	1028	1047	1005	1220
17	905	10.0	167	377	348	369	378
18	936	3.6	57	98	93	91	96
19	940	15.0	250	530	491	601	509
26	1375	6.0	150	229	255	236	295

Table 1: MODIS reflective solar bands (RSB) key specifications (center wavelength, typical scene radiance, and signal-to-noise ratio). Terra and Aqua MODIS on-orbit measured signal-to-noise ratio (SNR)

Figure 2: MODIS RSB calibrators: solar diffuser (SD) on the left and solar diffuser stability monitor (SDSM,) on the right

2.3 The Solar Diffuser and Solar Diffuser Stability Monitor System

The MODIS solar diffuser, shown in Figure 2, is a flat plate of space grade spectralon® which acts as a near Lambertian diffuse reflector. At the beginning of each RSB calibration, the solar diffuser door (SDD) is commanded to open position to permit incident sunlight to diffusely scatter from the SD and into the MODIS detectors via the rotating scan mirror. Due to the high gain of bands 8 through 16, direct solar irradiance on the SD causes detector saturation. For these bands an optional pinhole attenuation screen (the SDS, nominally 7.8% transmission) is added in the incident solar irradiance path. Therefore, two SD calibration events, one with the SDS open and one with the SDS closed, are combined to calibrate all the reflective solar bands.

The solar diffusers of both MODIS/Terra and MODIS/Aqua were calibrated pre-launch at Raytheon/Santa Barbara Remote Sensing (SBRS) using reference samples traceable to the National Institute of Standards and Technology (NIST)

reflectance standard. Figure 3 is a surface plot of the Terra MODIS solar diffuser BRF at the B8 center wavelength as a function of MODIS solar azimuth and elevation angles. On-orbit yaw maneuver observations verified the BRF in a relative sense for both Terra and Aqua.
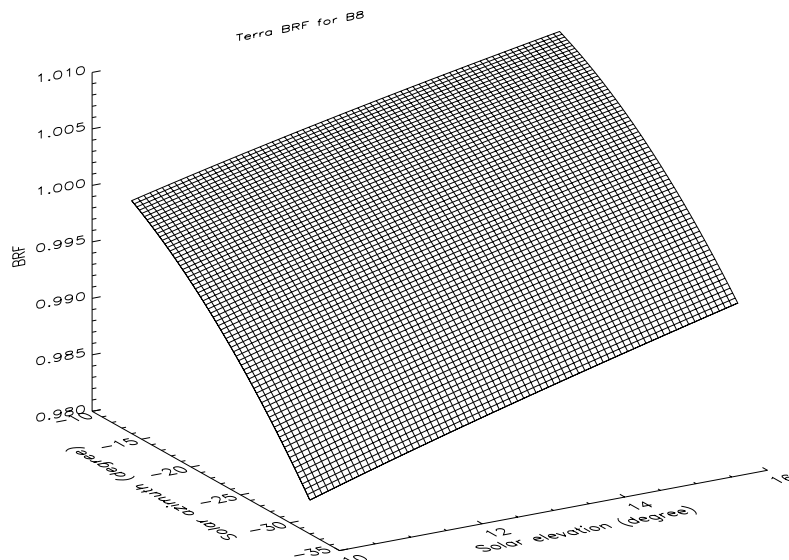

Figure 3: Terra MODIS solar diffuser bi-directional reflectance factor (BRF) as a function of solar azimuth and elevation angles at B8 center wavelength.

During on-orbit operation, the SD bi-directional reflectance factor (BRF) degrades. In order to measure the SD degradation a ratioing spectroradiometer, the solar diffuser stability monitor (SDSM) also depicted in Figure 2, is used together with the SD. During each SD calibration, the SDSM alternately measures the response of the SD view and the response of the direct Sun view. An attenuation screen of 1.44% nominal transmittance is used in the Sun view path so that the responses from both views are closely matched. The SDSM monitors the SD degradation using 9 individually filtered detectors. The wavelength of each SDSM detector and its corresponding MODIS band are summarized in Table 2. Detailed description of using the SDSM for the SD degradation and the early trending results of Terra MODIS SD degradation has been reported by Xiong *et. al.*[7,8].

SDSM Detector	Wavelength (nm)	Corresponding MODIS Band
D1	412.0	B8
D2	465.7	B3
D3	529.7	B11
D4	553.8	B4
D5	646.1	B1
D6	746.6	B15
D7	856.5	B2
D8	904.3	B17
D9	936.2	B19

Table 2: Solar diffuser stability monitor (SDSM) detectors wavelengths and their corresponding MODIS bands

3. CALIBRATION METHODOLOGY

3.1 Earth Scene Production Retrieval

The MODIS Level 1B algorithm converts the instrument response to an Earth scene to geo-located and radiometrically calibrated products for each band. The L1B primary data product for reflective solar bands (RSB) is the earth reflectance factor $\rho_{EV}\cos(\theta_{EV})$, which is given by

$$\rho_{EV}\cos(\theta_{EV}) = m_1 \cdot dn^*_{EV} \cdot d^2_{ES} \tag{1}$$

where θ is the solar zenith angle, m_1 is a calibration coefficient determined from the measurements of the SD and SDSM and updated constantly, d_{ES} is the Earth-Sun distance in AU at the time of the Earth view measurement, and dn^*_{EV} is the background subtracted, Earth view angle difference adjusted, and instrumental temperature effect corrected digital signal, evaluated by

$$dn^*_{EV} = (DN_{EV} - <DN_{SV}>) \cdot (1 + k_{inst} \cdot \Delta T) / RVS_{EV} \tag{2}$$

where DN_{EV} and DN_{SV} are earth view and space view raw digital numbers, respectively, k_{inst} represents the relative dependence of the digital number on the instrument temperature, ΔT is the difference of the instrument temperature from its reference value, and RVS is the response versus scan angle normalized at the angle of incidence (AOI) of the SD. For each band and detector, k_{inst} was calculated from pre-launch measurements using the detector s response at different instrument temperatures. RVS was measured pre-launch and updated from on-orbit characterization and monitoring[8]. For each frame of the EV scene, the calibration of Eqn. 1 is band, detector, sub-frame (for 250m and 500m bands), and mirror side dependent. Using the reflectance factor, the Earth view radiance can be calculated by

$$L_{EV} = e_{Sun} \cdot \rho_{EV}\cos(\theta_{EV}) / d^2_{ES}, \tag{3}$$

where e_{Sun} is the solar irradiance normalized with π at $d_{ES} = 1$ AU and is written as a global attribute in the L1B product so that the users can derive the RSB radiance product from the reflectance product if necessary. The solar irradiance is calculated by integrating the solar irradiance spectrum and prelaunch measured relative spectral response (RSR) for each detector.

3.2 SD/SDSM Calibration Algorithm

Rewriting Eqn. 1 for the sensor s SD observations, we have

$$\rho_{SD}\cos(\theta_{SD}) = m_1 \cdot dn^*_{SD} \cdot d^2_{ES} \tag{4}$$

or

$$m_1 = \frac{\rho_{SD}\cos(\theta_{SD})}{dn^*_{SD} \cdot d^2_{ES}} \tag{5}$$

where ρ_{SD} is the SD BRF, dn^*_{SD} is the corrected detector response to the SD view, and d_{ES} is the Earth-Sun distance in AU at the time of the SD measurements. The SD degrades on-orbit. Its degradation is tracked by the SDSM during each SD calibration. For high gain bands, a solar diffuser screen (SDS) is used for direct Sun light attenuation. Including these effects, Eqn. 5 becomes

$$m_1 = \frac{\rho_{SD}\cos(\theta_{SD})}{dn^*_{SD} \cdot d^2_{ES}} \cdot \Gamma_{SDS} \cdot \Delta_{SD} \tag{6}$$

where Γ is the vignetting function for the SDS closed mode (bands 8 through 16) and is unity for the SDS open mode (bands 1-7, 17-19, and 26) and Δ is the SD degradation factor determined from the SDSM[7]. The SD degradation is removed from each m_1 computation. The SDS vignetting function was determined on-orbit for Terra and Aqua from

yaw maneuver data and has the form of a 2nd degree polynomial. An additional empirical vignetting function that is determined each calibration from the ratio of SDS closed to SDS open for bands 1-4 and 17-19 is applied to the Terra m_1 factors for bands 8 through 16 as a function of time to remove higher order effects. Figure 4 is the Terra MODIS vignetting function for B8 determined from on-orbit yaw maneuvers.
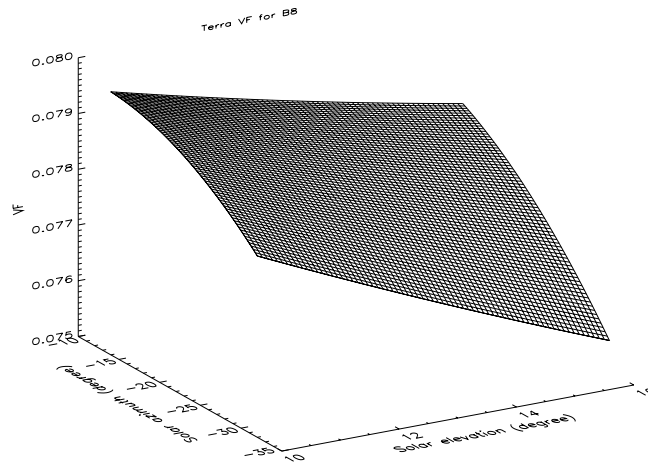

Figure 4: Terra MODIS solar diffuser screen (SDS) vignetting function (VF) for B8 as a function of solar azimuth and elevation angles at B8 center wavelength.

3.3 Calibration Coefficients Look Up Tables (LUTs)

For each SD calibration there are 1340 m_1 calibration factors. The LUT array is indexed by band, detector, sub-frame, and by mirror side. The calibration is performed offline and the coefficients are provided to the L1B through time-dependent LUTs. The SD BRF and SDS vignetting function shown in Figures 3-4, used for the offline m_1 calculation, are not included in the L1B code. RVS LUTs are also needed in the L1B. These are also time dependent[8].

4. MODIS RSB ON-ORBIT PERFORMANCE

4.1 RSB Signal to Noise Ratio

Terra MODIS has been in operation for more than 2.5 years, initially using the A-side electronics (A-I), and then B-side electronics (B). After the failure of the B-side power supply, the instrument went back to the A-side electronics. For SWIR bands, a different set of PFA bias voltages is used in the second A-side configuration (A-II). RSB signal to noise ratio (SNR) values for the middle detectors at these three configurations are provided in Table 1 for comparison with the specifications. Terra MODIS B7 SNR is out of specification. This was determined pre-launch. Also included in Table 1 are the corresponding Aqua MODIS RSB SNR values.

4.2 Aqua MODIS SWIR Bands Improvements

One of the improvements of Aqua MODIS over Terra MODIS is the reduction of the SWIR bands (5-7, and 26) electronic crosstalk and out-of-band (OOB) response. In Terra MODIS, the SWIR bands respond to thermal emission and the two sub-frames (B5-7) have different responsive behaviors. In Terra MODIS L1B, a thermal leak correction algorithm was implemented to reduce this effect. In Aqua MODIS, the effect is much smaller for B5 and B7. Using the SWIR bands response to the on-board blackbody at different temperatures, we can observe this effect and the improvement made in the Aqua MODIS. The comparison in Figure 5 shows substantial improvement for both B5 and B7 in terms of OOB response and reduction of the sub-frame differences. There is little change in band 26.
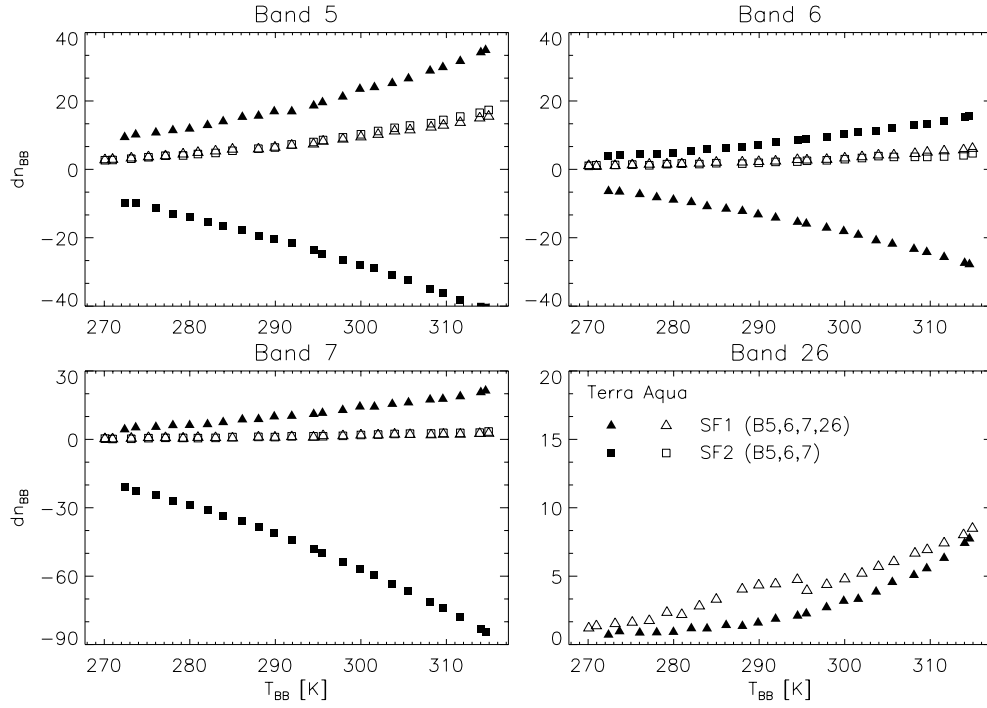
Figure 5: MODIS SWIR bands responses to the on-board blackbody at different temperatures. Comparison of Terra and Aqua MODIS out-of-band response and sub-frame differences for the 500m resolution bands (5-7)
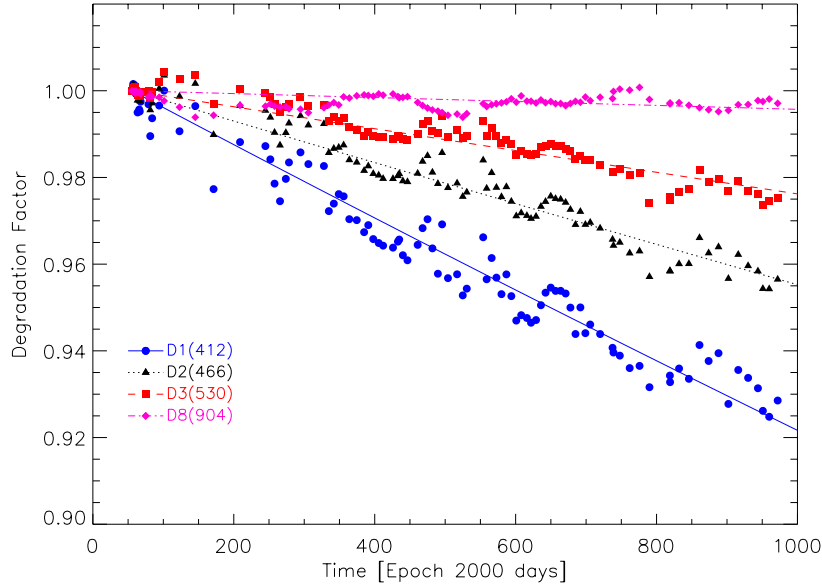

Figure 6: Terra MODIS solar diffuser on-orbit degradation trending results from SDSM detectors 1, 2, 3, and 8.

4.3 Solar Diffuser Degradation Trending

During each SD calibration, the SDSM collects data to monitor the SD degradation. It views the Sun light through an attenuation screen (different from the SDS) and the diffusely reflected Sun light from the SD. A detailed description of how the SD degradation is determined from SDSM on-orbit observations has been given by Xiong *et. al*.[7]. Figure 6

shows the Terra MODIS SD degradation at several SDSM wavelengths from over two and a half years of on-orbit measurements. Terra MODIS SD degradation is wavelength dependent with larger degradation at shorter wavelengths. The degradation of each MODIS band is derived from 9 SDSM detectors wavelengths through either interpolation or extrapolation. The SD degradation removed from each m1 calculation uses the value from the trending curve. SDSM D1 at 412nm has the largest fluctuation with an RMS of less than 0.6%.

4.4 Detectors Short-term Stability and Long-term Trending Results

Figure 7 illustrates the m_1 computation process: raw DN to dn and then to m_1. Only the central SD region with full solar illumination is used in the m_1 calculation. B3 does not use SDS and the scan by scan m_1 value is very stable. On the other hand, B8 needs SDS in the calibration and the m_1 value fluctuates from scan to scan due to residual SDS vignetting effects. The final m_1 value is frame and scan averaged during each calibration. This is a direct measure of the detector s short-term stability and other noise that could be introduced by the SDS.
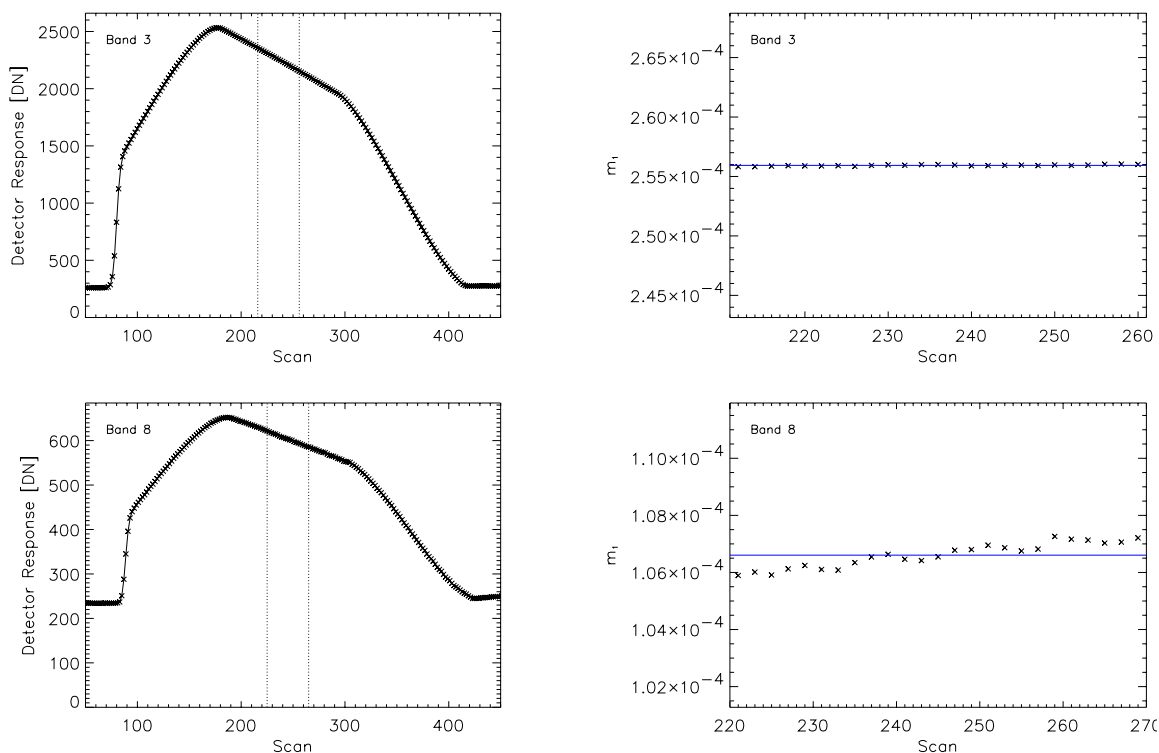

Figure 7: MODIS RSB m_1 computation examples. B3 does not use the SD screen while B8 uses the SDS in the calibration. Only a full solar illumination region (scans) is used in the m_1 computation

Figure 8 shows the m1 trending of the middle detector for bands 3, 8, 16, and 18. The solid curves with stars are values of m1 for mirror side one while the dashed curved with crosses are those for mirror side two. The curves clearly show that the two sides of the scan mirror have different reflectances and that they degrade differently. The m1 of bands 16 and 18, which have longer wavelengths compared to those of bands 3 and 8, are almost constant for two and a half years. The m1 of band 3 increases about 5% over two and a half years. Band 8 has the shortest wavelength and the largest increase of m1 in the period, which is about 10%. The m1 of the bands changes much faster in the early stages. There are three epochs in these trending curves. A normalization factor has been applied to remove the difference between A-side electronics and B-side electronics. The overall long-term response of Terra RSB is very stable. Aqua MODIS has been operational for less than 6 months. No long-term trending is shown in this paper.
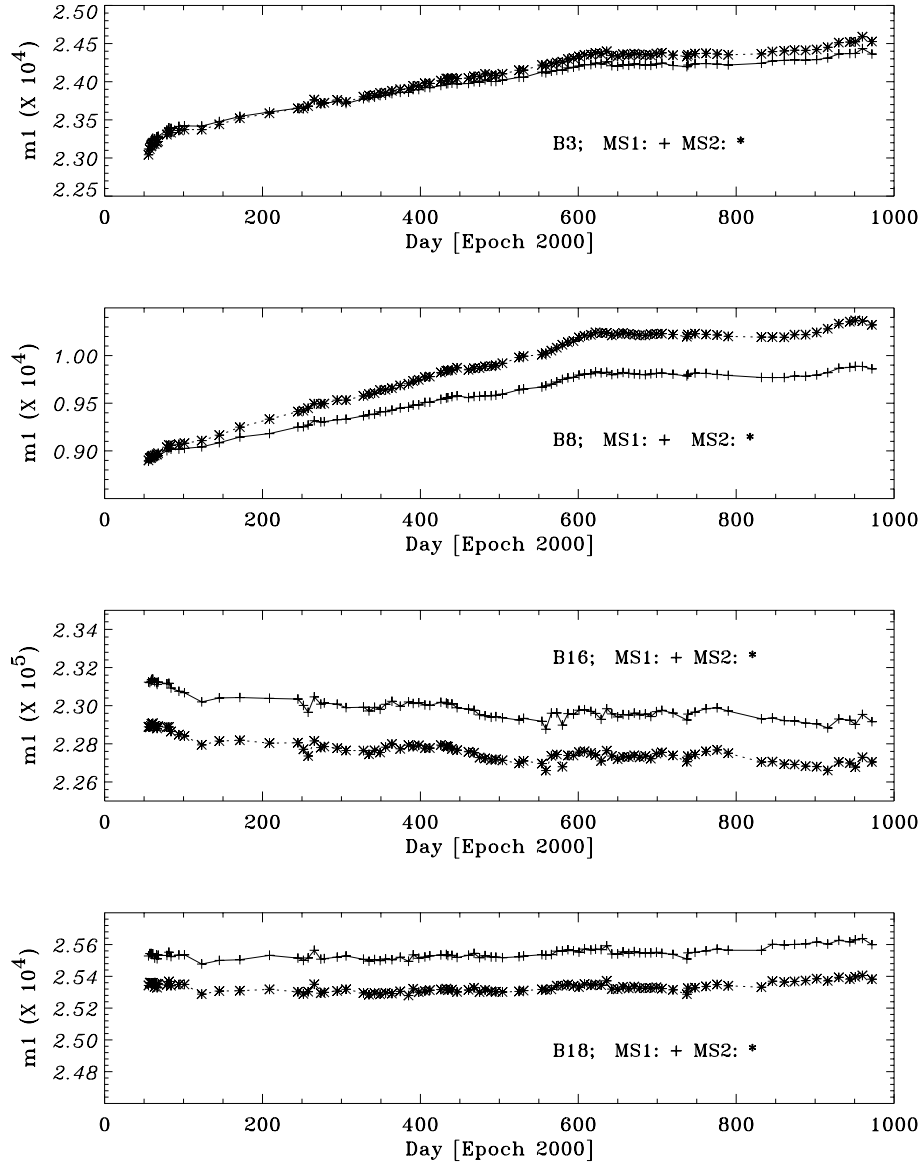
Figure 8: m1 trending of the middle detectors of the Terra MODIS bands 3, 8, 16, and 18: Solid line with crosses for mirror side one; Dashed lines with stars for mirror side two

5. SUMMARY

In this paper, we have described the MODIS reflective solar bands (RSB) on-orbit calibration using the solar diffuser and solar diffuser stability monitor (SD/SDSM) system. Issues of SD degradation and SD screen vignetting effects have been discussed and considered in the RSB algorithms. We have presented MODIS on-orbit performance in terms of RSB detector signal to noise ratio for both Terra and Aqua MODIS and compared these with the sensor s specifications. Using data from Terra MODIS, we have illustrated the SD degradation trending and the sensor s response trending, including short-term and long-term stability. Examples of Aqua MODIS performance improvements over Terra MODIS

are also given in terms of out-of-band response and sub-frame differences for the 500m bands. With both instrument operating and capable of viewing the same Earth scene from the morning orbit and afternoon orbit, better science products can be derived to further enhance our understanding of the global environmental system.

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